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ABSTRACT

R-11 was for many years the low pressure centrifugal refrigerant of choice. For environmental reasons, R-123 is now the low pressure centrifugal refrigerant of choice. Under current legislation, R-123 will be phased out by 2030. R-245ca has been proposed as a replacement for both R-11 and R-123 in new product and retrofit. This study compares measured performance of these three refrigerants in a 200 ton direct drive centrifugal chiller. The focus is on theoretical head requirements, measured onset of surge, adiabatic efficiency, impeller diameter effects and overall chiller performance. Conclusions include that R-245ca is not a suitable drop-in replacement for R-11 or R-123 due to surge concerns, but that it would be suitable in new product if the cost, availability and flammability issues can be resolved favorably.

INTRODUCTION

Federal regulations ban the production of CFC-11 after January 1, 1996. Distribution of HCFC-123 will be limited to service applications after January 1, 2020 and eliminated from production on January 1, 2030. HFC-245ca has been identified as a potential replacement for CFC-11 in retrofit applications and for HCFC-123 in new chillers. This report compares these three refrigerants based on their properties and their measured performance in a centrifugal chiller.

Centrifugal Compressors

Centrifugal compressors are not positive displacement devices but rather momentum devices, essentially high pressure fans. They raise pressure by means of accelerating a gas to high speed and then converting velocity pressure to static pressure. At the upper limit of pressure rise capability, centrifugal compressors will enter surge and suffer from oscillating backflow at the impeller outlet, a noisy and inefficient operating point. The pressure rise capability of a centrifugal compressor is a function of a number of variables, only two of which are relevant here: impeller tip speed (expressed as impeller diameter since rotational speed is constant) and the properties of the refrigerant. In this study a three stage compressor designed for CFC-11 was tested, the focus being on how the refrigerant properties and impeller diameters affect the predicted and actual performance.

Typical design conditions for a centrifugal compressor in water cooled air conditioning service are 40F (4.44C) saturated evaporator and 100F (37.77C) saturated condenser, a constant 60F (33.3C) lift. Table 1 below shows ideal cycle properties for three low pressure refrigerants to demonstrate the effect of the refrigerant.

Table 1. Comparison of ideal cycle properties for single stage compression.

	CFC-11	HCFC-123	HFC-245ca
Evaporator (saturated condition)			
Temperature - F (C)	40 (4.44)	40 (4.44)	40 (4.44)
Pressure - psia (kPa)	7.02 (48.40)	5.80 (39.99)	6.24 (43.02)
Sp. Volume - Ft3/lbm (M3/kg)	5.43 (.339)	5.90 (.368)	6.27 (.391)
Enthalpy - Btu/lbm (kJ/kg)	96.79 (225.1)	93.24 (216.9)	107.12 (249.1)
Entropy - Btu/lbm F (kJ/kg C)	.1966 (.823)	.1895 (.793)	.2176 (.911)
Sonic Velocity - Ft/sec (m/s)	443 (135)	414 (126)	441 (134)
Condenser (saturated condition)			
Temperature - F (C)	100 (37.77)	100 (37.77)	100 (37.77)
Pressure - psia (kPa)	23.46 (161.8)	20.77 (143.2)	22.86 (157.6)
Liquid Enthalpy - Btu/lbm (kJ/kg)	28.70 (66.75)	30.60 (71.17)	34.48 (80.20)
Isentropic Compressor Discharge			
Enthalpy - Btu/lbm (kJ/kg)	105.8 (246.1)	101.7 (236.5)	116.9 (271.9)
Cycle			
Refrig effect - Btu/lbm (kJ/kg)	68.09 (158.4)	62.64 (145.7)	72.64 (168.9)
Work Input - Btu/lbm (kJ/kg)	9.01 (21.0)	8.43 (19.6)	9.78 (22.8)
Coefficient of Performance	7.56	7.43	7.43
Suct'n Flow - Ft3/tn min (M3/mW S)	15.95 (2.14)	18.84 (2.53)	17.26 (2.31)

All three refrigerants show excellent coefficient of performance and so differences in efficiency can be expected to be small. HFC-245ca has the largest specific volume at the suction. But it also has the highest refrigerating effect and thus has the middle value for suction flow per unit of capacity. Since compressor capacities are based on their suction flow rate one would expect then that at equal suction conditions, CFC-11 would provide the highest capacity and HCFC-123 would provide the least.

HFC-245ca also has the largest work input requirement. Therefore, HFC-245ca will require the largest impeller diameter for a given lift. Conversely, given an existing impeller and rotational speed, HFC-245ca will support the smallest lift (temperature rise between evaporator and condenser). Working the above problem backwards, using the evaporator conditions of Table 1, applying the work input of CFC-11 and solving for condenser conditions yields Table 2 below.

Table 2. Comparison of properties at constant work input for single stage compression.

	CFC-11	HCFC-123	HFC-245ca
Condenser (saturated condition)			
Temperature - F (C)	100 (37.77)	104.6 (40.33)	94.8 (34.89)
Pressure - psia (kPa)	23.46 (161.8)	22.62 (143.2)	20.69 (157.6)
Isentropic Compressor Discharge			
Enthalpy - Btu/lbm (kJ/kg)	105.8 (246.1)	102.3 (237.9)	116.1 (270.0)
Work Input - Btu/lbm (kJ/kg)	9.01 (21.0)	9.01 (21.0)	9.01 (21.0)

Table 2 predicts that HFC-245ca has the lowest lift capability in an existing compressor and HCFC-123 has the highest. More specifically, these calculations estimate that the existing impellers can achieve lift to support 100F (37.8C) condensing temperature with CFC-11, 104.6F (40.3C) with HCFC-123 and only 94.8F (34.9C) with HFC-245ca. Assuming that 60F (33.3C) is the design lift requirement for CFC-11, diameters can be adjusted to hold this lift when using the other refrigerants. Work input is proportional to impeller tip speed squared. Since our impeller speed is constant (direct drive), tip speed, and therefore work input, is proportional to diameter squared. Therefore, if we take the average diameter of 24.83 inches (631 mm) with CFC-11 we can produce work input of approximately 9 Btu/lbm (21 kJ/kg). With 24 inch (610 mm) diameter impellers and HCFC-123 we can produce 8.43 Btu/lbm (19.6 kJ/kg) work input and the 60F (33.3C) lift. Or we can use 26 inch (660 mm) impellers with HFC-245ca. Using these relationships and factoring in manufacturing constraints, the diameters were chosen for their equal lift capability as noted below.

EXPERIMENTAL RESULTS

The test program was conducted with three refrigerants and three sets of impellers as shown in Table 3.

Table 3. Chiller Test Matrix

Impeller Diameter inches	Impeller Diameter mm	CFC-11	HCFC-123	HFC-245ca
26/26/26	660/660/660	X	X	X
25/25/24.5	635/635/622	X	X	X
24/24/24	610/610/610		X	

The evaporator leaving water temperature was held at 44 F (6.67 C) while water flow was held at 480 gal/min (30.3 l/s) for all tests. Condenser water flow was held at 600 gal/min (37.9 l/s) and entering water temperatures were varied from 70 F (21.1 C) up to the onset of surge or high pressure cutout in 5 F (2.78 C) increments for each of four inlet guide vane settings: 90, 70, 40 and 10 degrees. The highest condenser water temperatures reported were either at surge or just short of high pressure cutout.

Chiller Performance

Dropin. The test results confirm the predictions that the compressor lift capability is lowest for HCFC-123 and highest for HFC-245ca for constant diameter impellers. Thus, surge problems will occur in a drop-in retrofit with HFC-245ca in a chiller optimized and sized for CFC-11 or HCFC-123. The surge lines (entering condenser water temperature at the onset of surge vs guide vane position) for the 25/25/24.5 impellers (CFC-11 optimum) are plotted as the three solid lines in Figure 1, and confirm the lower surge limit for HFC-245ca. This will be a significant problem at full load (90 degree vanes) and over most of the operating range as the 5F (2.8C) margin over the ARI rating condition will be unacceptable to the customer. We conclude that drop-in conversions of low pressure chillers to use HFC-245ca are not commercially viable.

Dropin with diameter change. Diameter effects can be seen in the two dashed lines of Figure 1 which show performance of HCFC-123 with smaller impellers and HFC-245ca

with larger impellers. (Tests were conducted with the 24/24/24 impellers only with HCFC-123 because the others would surge at too low a temperature. Tests with the 26/26/26 impellers reached surge with HFC-245ca only, the others reaching high pressure cutout before reaching surge). These data show that by appropriately adjusting impeller diameters, loss of lift due to refrigerant change can be remedied.

How practical is an impeller diameter increase? While the effect of the different refrigerants has a fairly strong impact on capacity and power consumption in a drop-in situation, when diameters are selected for equal lift as they were in this series of tests, the efficiency differences essentially disappear as shown in Table 4.

Table 4. Chiller Full Load Performance - Properly Sized Impellers

	Impeller Diameters Inches	Condenser Entering Water Temp, F (C)	Capacity - Tons (kW)	Power - kW	Efficiency - kW/Ton (COP)
CFC-11	25/25/24.5	90 (32.2)	177.4 (623.7)	149.8	.84 (4.16)
HCFC-123	24/24/24	90 (32.2)	179.0 (629.4)	146.3	.82 (4.30)
HFC-245ca	26/26/26	90 (32.2)	186.0 (654.0)	155.1	.83 (4.22)
CFC-11	25/25/24.5	80 (26.7)	184.5 (649.0)	145.7	.79 (4.45)
HCFC-123	24/24/24	80 (26.7)	203.4 (715.1)	154.2	.76 (4.64)
HFC-245ca	26/26/26	80 (26.7)	220.2 (774.2)	168.4	.76 (4.60)
CFC-11	25/25/24.5	70 (21.1)	220.2 (774.2)	160.7	.73 (4.82)
HCFC-123	24/24/24	70 (21.1)	205.5 (722.5)	150.6	.73 (4.80)
HFC-245ca	26/26/26	70 (21.1)	245.2 (862.1)	176.5	.72 (4.88)

That's great! However, loading differences remain as shown in Figure 2. The middle curve represents the performance of the chiller with CFC-11 and its ideal diameter impellers. The other curves show two alternatives in changing from CFC-11 to HFC-245ca. The lower curve is for drop-in refrigerant replacement only with no impeller change. The upper curve shows conversion with impeller replacement to retain lift capability. In each case the 85F (26.7C) condenser entering water temperature point is noted and water temperature is increasing right to left in 5F (2.78C) increments with capacity and power consumption falling right to left. From this chart we can see that without impeller replacement capacity and power consumption are reduced and so motor capability is not a concern. However, with impeller replacement to maintain lift, the capacity and power consumption are increased relative to original conditions compelling an examination of motor capability. Thus we can see that, while impeller diameter can be used to control lift capability it cannot by itself keep all the performance measures at their original design values simultaneously.

We conclude that retrofits with HFC-245ca will require impeller replacement to retain lift capability. Retrofits may also need larger motors and power supplies, or alternatively, we could block the guide vanes so that electrical current limits are maintained.

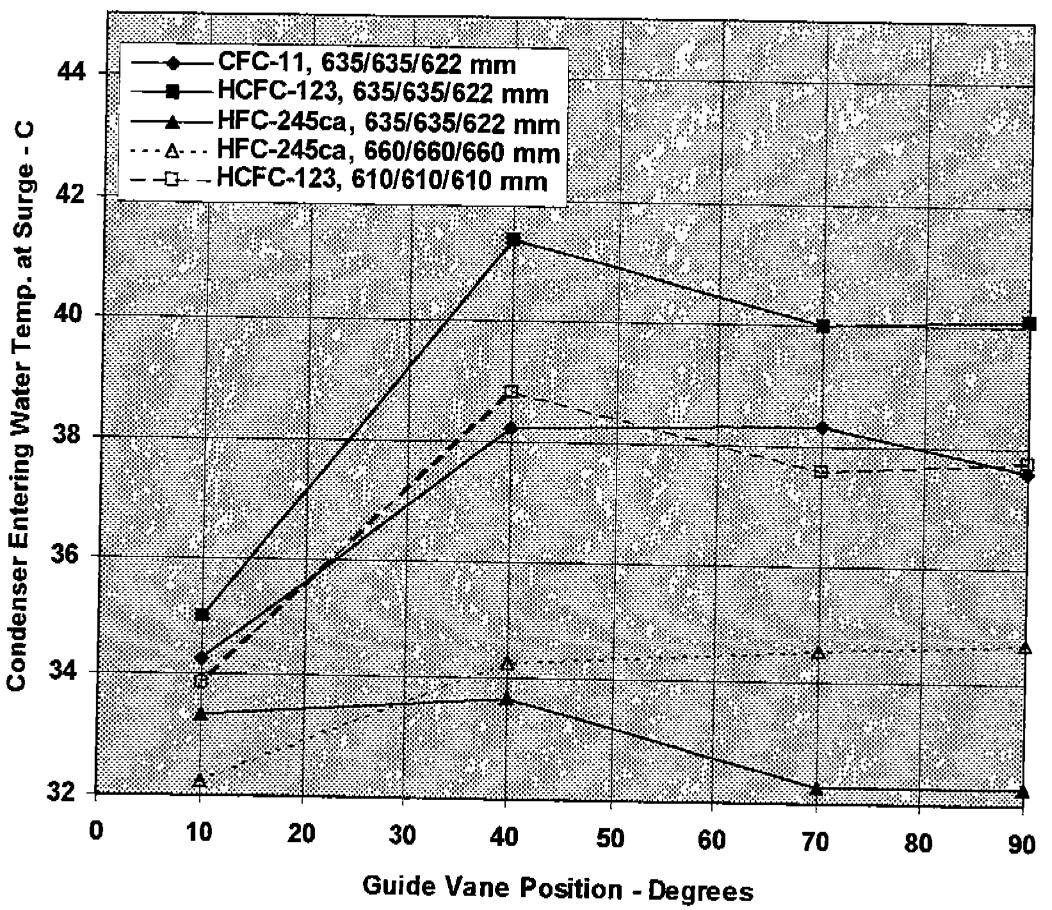
<u>Compressor Performance.</u> Using the data obtained from the 25/25/24.5 inch impellers, a compressor efficiency map (Figure 3) was constructed. These data show that over the tested range compressor efficiency is not strongly affected by refrigerant choice.

CONCLUSIONS

- HFC-245ca will not perform satisfactorily when substituted for CFC-11 or HCFC-123 in existing chillers with no hardware changes due to surge concerns. For HFC-245ca to perform satisfactorily in a retrofit situation, the compressor must be modified with larger impellers, will likely need a larger motor and drive system, and in many instances a new compressor casing. The high cost of replacing compressors and drive systems is justified in only special situations, and financial considerations drive most customers to the purchase of a new chiller.

- Chillers designed specifically for use with HFC-245ca can provide performance comparable to that for HCFC-123 chillers. This design is not commercially viable today because of the unavailability of HFC-245ca in cost effective commercial quantities, and the market resistance to refrigerants with Class 2 flammability ratings.

Fig. 1 Condenser Entering Water Temperature at Surge vs. Vanes



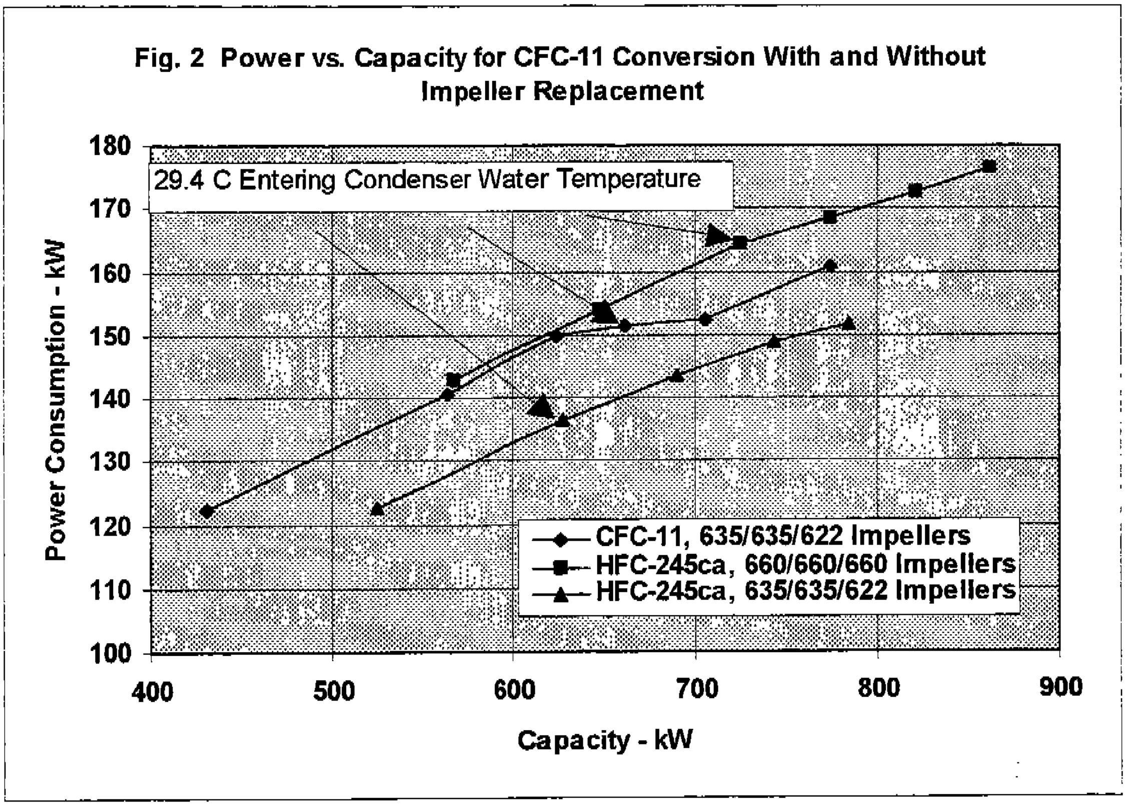


Fig. 2 Power vs. Capacity for CFC-11 Conversion With and Without Impeller Replacement
29.4 C Entering Condenser Water Temperature
Power Consumption - kW
180
170
160
150
140
130
120
110
100
400
500
600
700
800
900
Capacity - kW
CFC-11, 635/635/622 Impellers
HFC-245ca, 660/660/660 Impellers
HFC-245ca, 635/635/622 Impellers

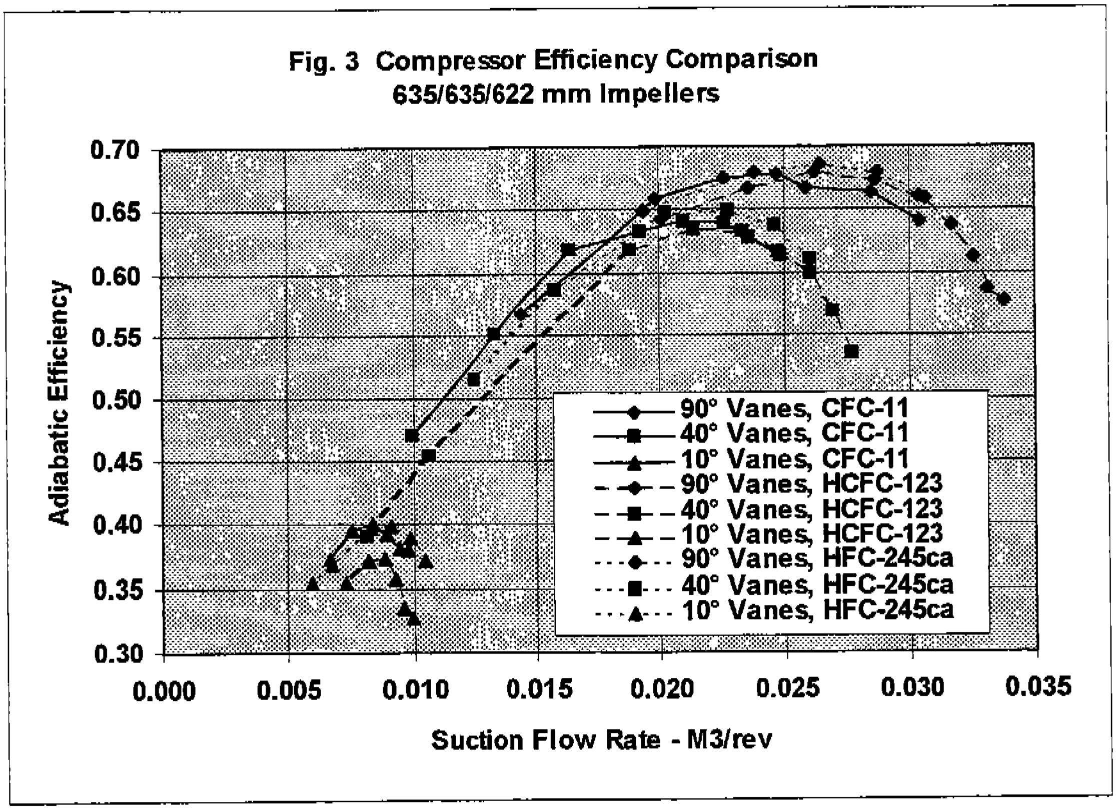


Fig. 3 Compressor Efficiency Comparison 635/635/622 mm Impellers
Adiabatic Efficiency
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
Suction Flow Rate - M3/rev
90° Vanes, CFC-11
40° Vanes, CFC-11
10° Vanes, CFC-11
90° Vanes, HCFC-123
40° Vanes, HCFC-123
10° Vanes, HCFC-123
90° Vanes, HFC-245ca
40° Vanes, HFC-245ca
10° Vanes, HFC-245ca